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CARBON FOOTPRINTING

Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components

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Abstract
Purpose This study analyzes the interrelated components in the production of a 5-cm caliper, field-grown, spade-dug *Acer rubrum* 'October Glory' tree in terms of their contributions to the carbon footprint, global warming potential (GWP), of this balled and burlapped product during production and its complete life cycle.
Methods The carbon footprint, greenhouse gas (GHG) emissions, associated with input materials and equipment use to produce this tree was expressed as global warming potential (GWP) in kilograms of CO_2 equivalence (CO_2e). A model system was defined encompassing production from rooting cuttings to finished product, the subsequent transport and transplanting in the landscape and the use and end-of-life phases. The model system was defined through nursery manager and arborist interviews and published production recommendations and good agricultural practices.
Results and discussion Including carbon sequestration during 1 year of liner production and 4 years of field production (0.366 and 12.1 kg CO_2e, respectively), the cutting-to-landscape GWP of the tree was calculated to be 8.213 kg CO_2e. Contributions to a tree's carbon footprint from input materials (2.85 kg CO_2e), fuel or electricity consumption during production (10.342 kg CO_2e), transport to the customer at a distance of 386 km (4.040 kg CO2e) and transport 32 km and transplanting into a landscape site (3.333 kg CO_2e) were calculated. Fuel and electricity consumption from cutting-to-landscape (17.715 kg CO_2e/tree) contributed 86% of the product GWP, before accounting for carbon sequestration during production. The weighted positive impact of sequestered carbon over a 60-year useful life in the landscape would exceed 901 kg CO_2e, less the 92.9 kg CO_2e required for removal and disposal.
Conclusions An LCA analyzing input components in field production of a shade tree will allow nursery managers to make informed decisions about the various operational elements. Individual variables that contributed most to model sensitivity included CO_2 sequestration during production and the use phase. Other important factors in the model included transport distance for the final product, fertilization, and equipment use for such activities as harvesting. The substantial weighted impact of carbon sequestration of the tree during the use phase would greatly outweigh carbon investment in its production, transport, transplanting, and disposal.

Keywords Carbon sequestration · Global warming potential · Greenhouse gas emission · Nursery crops

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1 Introduction

The environmental impact of the production and use of products in the market place is of increasing importance to consumers (Hall et al. 2010; Yue et al. 2010, 2011). This is often expressed as the sustainability of a product or service in terms of economic, environmental, and social considerations. Green is being used to describe more sustainable products. The production, use, and maintenance of landscape plants and floral crops have been described as the green industry. The industry increases the function and aesthetics of the built environment and improves the quality of life of the individuals in those environments as well as sequestering carbon and elevating O_2 in the environment. However, the choice of inputs in the production and use of

plants and related services and the adaptive plant functions in changing environments will determine the degree of sustainability of the green industry (Marble et al. 2011; Prior et al. 2011).

Life Cycle Assessment (LCA) can be used to analyze components of agricultural production systems and systems as a whole (Hayashi 2006). The procedures have been applied to comparative studies of the agricultural phase of biofuels (Farrell et al. 2006; Liebig et al. 2008; Davis et al. 2009; Debolt 2009) and to compare organic and non-organic production systems (Nemecek et al. 2005; Nemecek et al. 2006 Williams et al. 2006). LCA has been used to estimate environmental impact on an individual farming operation and on a regional, country, or global scale (Payraudeau and van der Werf 2005; Koerber et al. 2009). Emissions estimated for various farming operations have been reported (West and Marland 2000, 2003; Lal 2004).

Input materials, with a defined carbon footprint, used in the production of a plant must be inventoried and expressed in terms of a functional unit of the final product. Fertilizers and the use of machinery have been identified as significant GHG contributors (Lal 2004; Nemecek et al. 2005). Nitrogen fertilization in particular has been identified as a significant component of the carbon footprint of various cropping systems (Hillier et al. 2009). Although the production, transportation, and application of fertilizers use energy and result in greenhouse gas emissions, these data must be considered in relation to increased carbon sequestration through enhanced crop growth stimulated by the fertilizer (Brentrup and Palliere 2008). As one would expect, the use of machinery has also been identified as a major contributor to the carbon footprint of farming operations (West and Marland 2002). The use of plastics to cover greenhouses and for containers provide a significant portion of the carbon footprint for floral crops (Russo and Mugnozza 2005; Russo et al. 2008a, b; Russo and De Lucia Zeller 2008). CO_2 emissions in the 47 to 133 kg CO_2e range per 1,000 forest seedling in a production system in Sweden has been reported (Aldentun 2002) as well as an inclusive LCA of walnut seedling production strategies in Italy (Cambria and Pierangeli 2011). Kendall and McPherson (2011) reported that 4.6 and 15.3 kg CO_2e were emitted in production and distribution of a container-grown tree in a no. 5 and a no. 9 container, respectively. Their model system included an intensive container nursery and did not include sequestered carbon during production.

Unlike many targets of LCA studies, the carbon footprint of crops must not only account for the energy and carbon inputs but must quantify CO_2 fixed by plants during production and use phases as related to a 100-year assessment period. Carbon sequestration during production is an important component of nursery crop production systems (Marble et al. 2011). Carbon sequestration, lowered energy demand for heating and cooling interior spaces and other environmental services by urban trees in their use phase have been well documented (USDOE 1998; McPherson et al. 2007; McHale et al. 2009). Trees also sequester carbon during the production phase, proportional to their leaf area, mass, and growth rate. Although not included in this study, the indirect benefits of trees during their use phase on atmospheric CO_2 include shading to reduce energy consumption for cooling buildings (McPherson et al. 1999) and their impact on the albedo of the landscape, which was recently reported to be a major factor in global climate trends (Loarie et al. 2011).

2 Methods

2.1 Goal, scope, and functional unit

The purpose of this study was to analyze a defined life cycle for a field-grown maple tree in the lower Midwest of the USA and to estimate the environmental impact, specifically the carbon footprint, of the overall production system and individual components of that system. The scope also included the use and end-of-life phases. The functional unit is a field-grown, spade-dug, 5-cm caliper *Acer rubrum* 'October Glory' tree with a height of 3.6 to 4.3 m and a 61-cm diameter root/soil ball (American Nursery and Landscape Association 2004).

2.2 System boundaries and assumptions

The boundaries for this assessment included the rooting of a cutting in ground beds and field production of a 2-m tall liner in one nursery, transporting the liner to another nursery where a 5-cm caliper tree would be finished. Following harvest and loading on trucks for delivery, the tree would be transported to a landscape site for transplanting. A 60-year functional life would be followed by tree removal and disposal to complete the life cycle (Fig. 1).

Emissions associated with the production of capital goods, such as buildings and machinery, were not included in the study as per PAS 2050, Section 6.4.3 (PAS 2050 2008). This study was conducted in accordance with the International Organization for Standardization's Life Cycle Assessment, Requirements and Guidelines 14044:2006 (ISO 2006) and the British Standards Institute's specifications in PAS 2050:2008 (PAS 2050 2008). Production protocols for field production of shade trees differ significantly between nurseries, even within a state or region. A representative model system for this study was determined through interviews with nursery managers in Kentucky and Tennessee with experience in producing field-grown *A. rubrum* "October Glory" and consistent with general recommendations (Halcomb 2011). The time required for defined machinery to perform specific

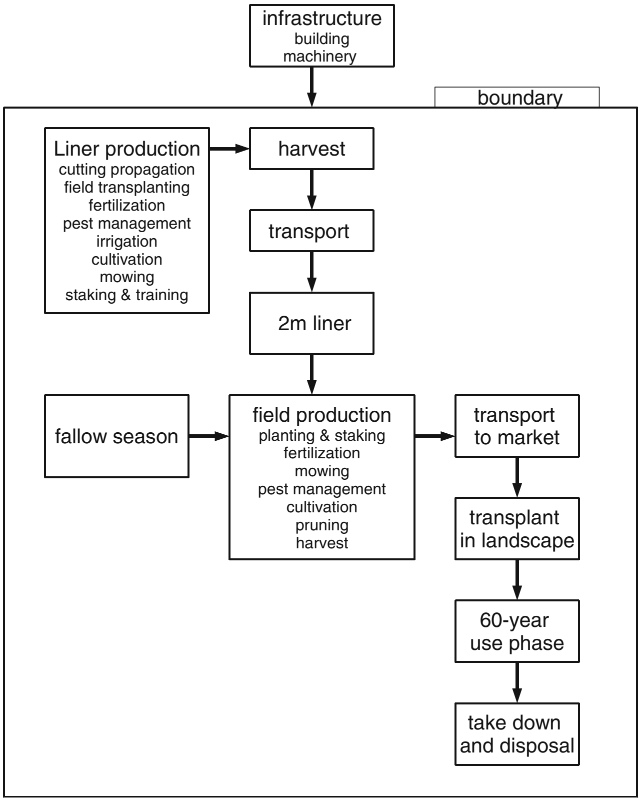

Fig. 1 System diagram and boundaries

operations as well as the quantity of materials used in fertilization, pest management, staking, and harvesting operations were estimated from the nursery manager records and manufacturer recommendations. Each of the nursery managers interviewed indicated that these farms had been in agricultural production for more than 50 years, at least the past 20 years in nursery crop production. Tobacco and forage crops were predominant before shifting to nursery crop production and forage grasses cover 63% of the field surface during nursery production and 100% in the fallow year. Therefore, impact of land use change was not included in this analysis as per PAS 2050 (PAS 2050 2008).

The model system was based on the production of a branched, bare-root, 2-m liner from a cutting in one nursery (liner nursery) and transporting to another nursery (field nursery) for finishing. Liner production would involve rooting cuttings in a ground bed in May and transplanting to the field the following May for one growing season. Liners would then be dug bare root in the fall, overwintered in a barn and trucked to the field nursery in April. The field block at the second nursery (field nursery) would have previously remained fallow with a sudex cover crop for one growing season that was plowed under in the fall. A 5-cm caliper tree would be harvested from the field nursery in the fall of the fourth year. Therefore, the entire production phase would include 2 years in the liner nursery plus almost 4 years in the field production nursery. The harvested tree would be transported to a landscaper who would transplant it into a suburban site with favorable growing conditions. Following a 60-year use phase, the tree would be taken down, chipped, and used as mulch.

2.2.1 Input materials and equipment use in liner production

A fresh 5-cm layer of sand would be added to a 1×9.1-m ground bed following tilling. The sand was assumed to be transported 38.6 km to the nursery in a dump truck. Hormodin no. 3 with Captan would be applied to 3,780 cuttings before sticking into the sand bed. Fungicides and insecticides would be applied at the middle of the recommended rate range with a backpack sprayer. Fungicides would include two applications each of thiophanate-methyl, chlorothalonil, and mancozeb. Two applications of the insecticide bifenthrin and one application each of acephate and malathion would be made. A mist system with a 1-hp electric pump would be operated a total of 15 min/day for 180 days and cover 60,000 cuttings (16 beds). Rooted cuttings would be overwintered in the ground bed with a 6-mil white polyethylene cover (assumed to last 3 years) supported by welded wire mesh. Rooted cuttings would be harvested in May of the following year by undercutting the bed with a band blade and plants would be transplanted immediately into the field. Shrinkage was assumed to be 25%.

The liner field plot would be prepared by turning once with a moldboard plow, disking three times, and tilling once with a roto-tiller. Rooted cuttings would be transplanted from the ground bed to the field plot on18-cm centers in rows spaced 1.8 m apart at a rate of 1,000/h. Each row would contain 3,000 rooted cuttings and occupy 0.10 ha. A 4.3-m roadway spaced at every six rows was assumed. Two-meter bamboo stakes would be inserted into the ground at each rooted cutting and secured with plastic bands as the trees grew. Fungicides and insecticides would be applied at the middle of the recommended rate range with an airblast sprayer (280 L of spray/ha). Fungicides would include two applications each of chlorothalonil and mancozeb. Three applications of bifenthrin, acephate and malathion and two applications of carbaryl were assumed. The herbicides oryzalin, isoxaben, glyphosate, and sethoxydim would each be applied once. Row middles and the roadway would be mowed four times with 24- and 89-hp tractors, respectively. Weekly irrigation provided via a drip irrigation system was assumed. Trees would be fertilized twice with 13-13-13 at a 114 kg N/ha rate banded in rows. Trees would be harvested using a u-blade at a rate of 500 trees/h. Harvested trees would be graded and stored in an unheated barn before being loaded 4,000 trees per heavy truck load and transported 400 km. Travel distances were established through nursery manager interviews. Shrinkage in this stage was also assumed to be 25%.

2.2.2 Inputs for field production phase of the finished tree

A sudex cover crop would be established in the nursery field between successive crops. This would include field preparation using a moldboard plow and disk harrow, seeding with a grain drill and plowing under with a moldboard plow in the fall. In the spring of the following year, the field would be cultivated with a chisel plow and disk harrow in preparation for transplanting and staking tree liners. Liners would be transplanted at 1,976 plants/ha, spaced 1.8 to 2.1 m within rows 3.3 m apart. A 1.2-m-wide vegetation-free band would be maintained for each row. Grass seed (tall fescue) would be sown and sod maintained between the rows. The trees would be grown for approximately 44 months, extending through four growing seasons. Activities, with input materials, for routine fertilization, pruning, spraying, and mowing would be performed. It was assumed that without insect control measures, the trees would not be saleable and the regimen defined here would be normally required in conjunction with an effective scouting program. A combination of cultivation, mowing, and herbicide applications would be required to maintain acceptable weed management for producing a saleable tree. A finished tree would be dug with a tree spade on a skid-steer loader and placed in a burlap-lined, wire basket, secured with nylon twine. Five percent of trees would not be harvested due to plant death or unacceptable quality (1,877 marketable trees/ha). The calculation of the final carbon footprint included the carbon investment in the liner production spread across the marketable 5-cm caliper trees.

Input materials would include the following. Fertilization: ammonia nitrate at 95.5 kg/ha, banded in-row (25% of area) twice per year for 3 years. Fiberglass stake: 1.2 cm× 3.05 m (0.771 kg), used for the first year of production, with a life of 20 years. Pesticide application rates were assumed to be the middle of the recommended range. Herbicide applications: pendimethalin+simazine applied annually for years 2, 3, and 4 and glyphosate applied as a directed spray three times annually. Insecticide application: cyfluthrin applied annually for 3 years; abamectin and imidacloprid/cyfluthrin applied twice annually for 3 years; and permethrin applied three times annually for 3 years. A 61-cm wire basket (0.626 kg) with a 137×137-cm flat burlap liner would be secured with 9.1 m of nylon twine and 20 staples (0.014 kg) and a corrugated cardboard trunk protector installed (0.0113 kg) at harvest.

2.2.3 Assumptions for equipment use in both liner production and field nursery production phases

The model system included the use of motorized machinery for the performance of the described activities. It did not account for activities requiring labor but not utilizing motorized equipment. Tractors of various horsepower rating were matched to the various functions. The portion of expected load and throttle for specific operations were assumed to be: land preparation, 80-hp tractor at 0.85 load and 0.85 throttle; mowing, 43 hp (field production) or 24-hp (liner production) tractor at 0.85 load and 0.85 throttle; spraying and cultivation, 24, 43, or 80-hp tractor (depending upon application) at 0.85 load and 0.85 throttle; transplanting in the liner nursery, 24-hp tractor at 0.5 load and 0.5 throttle; spraying in the liner nursery, 24 or 80-hp tractor at 0.85 load and 0.85 throttle; fertilization and staking/pruning, 43-hp tractor at 0.50 load and 0.50 throttle; skid steer with tree spade, 75 hp at 0.85 load and 1.0 throttle; hauling trees or liners from the field, 80-hp tractor at 0.5 load and 0.5 throttle; and pushing and disposing of culls, 80 hp at 0.85 load and 1.0 throttle.

2.2.4 Assumptions regarding post-harvest transport, transplanting in the landscape and use phase

Emission estimates for transporting finished trees from the nursery to the customer were based on fuel use and the assumption of 100 trees per heavy truck (2.55 km/L of diesel) traveling 386 km. A light truck and trailer (4.3 km/L of diesel) for transporting eight trees to a landscape site at a distance of 32 km was assumed. Traveling distances were established through interviews with nursery managers and are representative of the majority of trees sold. It was assumed that a 35-hp tractor (3.6344 L/h of diesel) would be used for 5 min to position the tree at the landscape site. The tree would be transplanted into a site with good growing conditions for a 60-year useful life with minimal maintenance supplied by the land owner. Based on interviews with three certified arborists, it was assumed that end-of-life actions would include an arborist's crew traveling 40 km in a heavy duty truck, using a chainsaw for 3.5 h to take-down and cut-up the tree and a 140-hp chipper for 2 h to chip the tree into mulch for municipal use.

2.3 Inventory analysis and data collection

The GHG emissions, expressed as the global warming potential (GWP) per kilogram of CO_2 or equivalence (CO_2e), of the equipment and trucks used in this system were estimated based on the fuel consumption calculations and assignment of expected GHG emissions from those operations. Diesel consumption for tractors was estimated using the American Society of Agricultural and Biological Engineers' Standards published in 2009 and applied in a Virginia Cooperative Extension Service publication (Grisso et al. 2010), allowing for expected load and throttle for each operation expressed as a portion of full load and throttle capacity of each tractor. Diesel consumption rates used for

heavy trucks, light trucks and the chipper were 6 km/L, 4.2 km/L, and 7.6 L/h, respectively. The GWP factors for fuel consumption were assumed to be 2.668 kg CO_2e/L of diesel and 2.324 kg CO_2e/L of gasoline, according to US Environmental Protection Agency (USEPA 2005).

The annual energy use for general overhead for the field nursery (office, shop, etc.) was estimated to be 1.18 kw h of electricity (18,000 kw h for a 40-ha nursery) and 0.12450 L of gasoline (37.85 L/week for farm trucks). The liner nursery overhead energy use was assumed to be half that amount. Greenhouse gas emissions were assumed to be 0.67 kg CO_2e/kwh for electricity consumption (Samaras and Meisterling 2008).

The GWP of input materials were determined as follows. Lal (2004) estimated the average herbicide, insecticide, and fungicide to have total C emission equivalents of 6.3±2.7, 5.1±3.0, and 3.9±2.2 kg/kg active ingredient (a.i.), respectively, and reported C emission equivalents for specific pesticides as 9.1, 4.6, and 3.1 kg C-equivalent/kg a.i for glyphosate, malathion, and carbaryl, respectively. These emission values in C equivalence were converted to CO_2 equivalence by multiplying them by 3.664 and used in this study. Calculating from GREET 1.8a (Wang 2007), Snyder et al. (2009) reported a GWP for manufacturing and transportation for ammonium nitrate (9.7 kg CO_2e/kg N), urea (3.2 kg CO_2e/kg N), P_2O_5 (1.0 kg CO_2e/kg), and K_2O (0.7 kg CO_2e). These values were used in this study. A default coefficient for fertilizer-induced N_2O emission from soils, assuming a loss of 1% of N applied (IPCC 2006), was used by Snyder (Snyder et al. 2009) to calculate an additional GWP of 4.65 kg CO_2e/kg of N applied. That value is highly variable with little documented differences due to fertilizer type, but was assumed in the current LCA for urea and ammonium nitrate N sources.

The GWP for steel wire for the wire basket and wire staples to fasten the burlap was assumed to be 1.2927 kg CO_2e/kg based on LCA data provided by the World Steel Association via personal communication. Their data assumes that recycled steel in manufacturing the basket and recycling a portion of used baskets. A GWP factor of 0.47 kg CO_2e/kg was used for the trunk protector as obtained from Sourcemap (http://www.sourcemap.org/parts/cardboard-virgin) for corrugated card board made from wood. A GWP for structural fiberglass of 2.0646 kg CO_2e/kg, derived from a professional LCA comparing building products (http://www.strongwell.com/pdffiles/green/Life-Cycle-Report.pdf), was assumed. The carbon footprint of sand was assumed to be 0.0016 kg CO_2e/kg (http://www.mecin.com.au/BC%20Maintenance%20Carbon%20Footprint%20Foundry%20Sand%20v3_1.pd) plus 0.002 CO_2e/kg for transporting 39 km to the nursery for a total of 0.004 kg CO_2e/kg sand. The GWP of white poly row cover was assumed to be 1.5 kg CO_2e/kg of product (http://www.entrepreneur.com/tradejournals/article/205091797.html). A bamboo stake was assumed to have a carbon footprint of 0.02 kg CO_2e (Kendall and McPherson 2011) but would be used for three crops. West and Marland (2002) reported a carbon footprint of orchardgrass seed of 1.11 and 0.54 kg CO_2/kg for ryegrass seed. In the absence of data specific for sudex and fescue seed, 1.11 kg CO_2e/kg was used in this study. There were 0.638 kg of burlap and 0.045 kg of nylon twine used per harvested tree; however, these were not included in the analysis due to the lack of specific data and the negligible impact of these materials on total GWP. The rooting hormone talc used on cuttings was assumed to be negligible and excluded from the analysis.

Many LCAs of farming operations have failed to consider the carbon captured by the growth of the crop (Mourad et al. 2007). In this study, sequestration during production was calculated directly from mean dry weights of red maple trees as a liner and was calculated using a growth model for the finished product. Carbon sequestration during the final year of the 2-m liner production phase (0.366 kg CO_2/liner) was calculated assuming 200 g of dry weight accumulation. Unpublished mean dry weight of ten branched, bare-root *A. rubrum* liners with a 2±0.2 m height averaged 248.6±41.7 g (personal communication with J. Owens, Virginia Tech Horticulture, 2011). Using the Ter-Mikaelian equation as published in the CUFR Tree Carbon Calculator (Center-for-Urban-Forest-Research 2008), the above ground dry weight of the finished 5-cm caliper tree was calculated. The above ground dry weight was divided by 0.78 to determine the total dry weight of tree (Peper et al. 2009). Twenty percent of the root dry weight was assumed to be left in the field upon harvest (Gilman and Beeson 1996). Fifty percent of tree dry weight is carbon, which was multiplied by 3.664 to determine the kilogram of CO_2 sequestered (McPherson and Simpson 1999).

As trees in the landscape grow, carbon is sequestered at a rate based on increasing dry weight accumulation (McPherson and Simpson 1999). An *A. rubrum* transplanted into a lower Midwest USA, suburban landscape as a 5-cm caliper tree, according to the CUFR Tree Carbon Calculator calculation method (Center-for-Urban-Forest-Research 2008), would sequester 3,632 kg CO_2 in 60 years. This value does not include the indirect savings of energy, and subsequent carbon emission reduction, in cooling and heating buildings when trees are selected and strategically placed to reduce heat load and wind speed at buildings. Nor does it include the carbon investment in tree maintenance and removal at end of life. However, not all the of carbon taken out of the atmosphere by the tree would have been sequestered for the full 60 years of useful life and that time is less than the standard 100-year assessment period (PAS 2050 2008). There is value in removal of CO_2 from the atmosphere for up to 60 years even though stored carbon would be released at the end of life. Therefore,

the weighted average GWP impact of stored carbon from annual sequestration relative to a portion of the 100-year assessment period was calculated using the growth curve for red maple in the CUFR Tree Carbon Calculator and protocol described in Appendix C of PAS 2050. This procedure accounts for the fact that CO_2 sequestered in year 1 would be stored throughout the 60-year life of the tree in the landscape but the CO_2 sequestered in year 50 would be stored for only 10 years of the 100-year assessment period.

Sensitivity analysis was conducted to evaluate the relative impact of input variable errors as well as the impact of each input variable on the total kilogram of CO_2e investment in the tree. Each input variable within each life phase was in turn increased by 10%, while other variables were unchanged in model simulations. The maximum percentage change in total kilogram of CO_2e investment in the tree was used to assess the sensitivity of the model to each variable. The sensitivity of CO_2 sequestration during production, use, and end-of-life phases was calculated separately using the same procedures. Sensitivity for each phase was expressed relative to the final carbon footprint.

3 Results and discussion

The estimated carbon footprint of a 5-cm caliper *A. rubrum* 'October Glory' produced in the lower Midwest when leaving the nursery (cutting-to-finished tree) was 0.840 kg CO_2e, including carbon sequestration during production. Transporting and transplanting to the landscape added 7.373 kg CO_2e. The total cutting-to-landscape carbon footprint was estimated to be 8.213 kg CO_2e. Input materials and equipment use in the two nurseries contributed 12.106 kg CO_2e/tree. The contribution of field machinery use alone was 9.254 kg CO_2e/tree. The general nursery overhead from electricity and gasoline consumption at the two operations accounted for 1.088 kg CO_2e/tree.

Based on expected dry weight accumulation, each tree would sequester an estimated 12.1 kg CO_2 during the final four growing seasons of field production and 0.366 kg CO_2 during the final year of liner production. The 12.1 kg CO_2 is in general agreement with those determined with other published models. Estimated CO_2 sequestered during 4 years of field production (assumed 1.95-, 2.54-, 3.81-, and 5.08-cm caliper trees in corresponding years) were 1.32, 2.92, 3.83, and 5.01 kg CO_2, respectively, for a total of 11.88 kg CO_2 per tree using the iTree tool (http://www.itreetools.org/design.php). Total CO_2 sequestered during field production utilizing a published method by the U.S. Department of Energy (USDOE 1998) for urban trees was estimated for red maples during the 4-year production cycle to be 20.6 kg CO_2 per tree. Additional research to address the fate of carbon in roots left in the field and to measure the dry weight of harvested trees would add precision to future assessments.

The carbon footprint for each 2-m bare-root liner was 0.134 kg CO_2e/liner. This value represents the contributions of equipment use (0.276 kg CO_2e), input materials (0.115 kg CO_2e), transportation of the liner to the field nursery (0.105 kg CO_2e), and general overhead (0.004 kg CO_2e) minus the carbon sequestered in the liner during production (0.366 kg CO_2). Equipment use during production and transporting the finished liner contributed 55% and 21% of the liner carbon footprint, respectively. Fertilizer and pesticides contributed 0.097 and 0.015 kg CO_2e of emissions from the input materials per liner, respectively.

GWP attributed to material inputs during field production totaled 2.736 kg CO_2e/tree plus 0.142 kg CO_2e from the liner (Table 1) and equipment use added 8.979 kg CO_2e/tree (Table 2). Material inputs other than pesticides during field production accounted for 2.535 kg CO_2e/tree. Fertilizer (1.449 kg CO_2e) and the wire basket (0.843 kg CO_2e) accounted for 2.292 kg CO_2e or 84% of the carbon footprint of input materials during the field production phase. Still, all material inputs (not including the liner) accounted for only 21% of total GWP investments during field production (12.798 kg CO_2e/tree).

The control of insect pests and weeds in field-grown maple trees is necessary for production of a marketable product. The rates and applications of pesticides used in this study were consistent with good agricultural practices, including scouting for pests (Fulcher 2009). The GWP of pesticides applied during the field production phase was 0.201 kg CO_2e/tree or 7% of carbon investments for input materials, excluding the liner. Although pesticides differ in their carbon footprint and using an industry average reduced the potential precision of this study, such information on many pesticides is simply not publically available. However, even if the GWP factor was twice the published average value used in this study, pesticide contribution to the tree GWP would still be relatively small. This relatively low contribution of pesticides to the carbon emissions in crops has also reported by others (Russo et al. 2008a; Russo and De Lucia Zeller 2008; Hillier et al. 2009).

Contributions of equipment use for specific operations in the field nursery to GWP are presented in Table 2. GHG emissions from the use of diesel-powered equipment would account for 70% of the total GWP investment during the production phase of a 5-cm caliper, field-grown red maple and 70% of that occurs at harvest. Equipment use for cover crop production, land preparation, transplanting, and seeding between rows for the field production phase contributed only 0.243 kg CO_2e/marketable tree. Equipment use for pruning, staking, fertilization, mowing, cultivation, and herbicide and insecticide applications accounted for 1.958 kg

Table 1 Contribution of input materials (including liner) during the field production phase to the carbon footprint (global warming potential, GWP, kilogram of CO_2e) of a 5-cm caliper, spade-dug, red maple tree

Liner input to field production	Liner/ha	Liner/marketable tree[a]	GWP[b] (kg CO_2e/liner)	GWP/marketable tree (kg CO_2e)
2-m Bare-root liner	1,976	1.0527	0.1345	0.1416
Input material	Product/ha (kg)	Product/marketable tree[a] (kg)	GWP (kg CO_2e/kg)	GWP/marketable tree (kg CO_2e)
Sudex seed—fallow year	45.60	0.0243	4.067	0.0988
NH_4NO_3; twice/year; 3 years	572.85	0.3051	4.75	1.4492
Fescue seed—between rows	17.10	0.0091	4.067	0.0370
Fiberglass stake; use 1 year; 20-year life	98.80	0.0406	2.0646	0.0838
Wire basket (recycled steel)	1,223.80	0.6520	1.2927	0.8429
Wire staples	26.28	0.0140	1.2927	0.0181
Trunk protector	21.30	0.0114	0.47	0.0054
Input material (pesticides)	Product/ha (L)	Active ingredient/marketable tree (kg a.i.)	GWP (kg CO_2e/kg a.i.)[c]	GWP/marketable tree (kg CO_2e)
Cyfluthrin; once/year; 3 years	2.9652	0.000189	18.6864	0.0035
Abamectin; twice/year; 3 years	0.78924	0.000008	18.6864	0.0001
Imidacloprid/cyfluthrin (foliar); twice/year; 3 years	3.2885	0.000064	18.6864	0.0012
Permethrin; three times/year; 2 years	6.31392	0.001254	18.6864	0.0234
Pendimethalin; once/year; 3 years	7.34431	0.001484	23.0862	0.0343
Simazine; once/year; 3 years	4.16542	0.000943	23.0862	0.0218
Glyphosate; three times/year; 3 years	15.78478	0.003498	33.3424	0.1166
Total kg CO_2e/tree				2.8777

[a] Assuming 5% shrinkage due to plant dead or unacceptable quality from total of 1,976 trees/ha

[b] Fuel and electricity consumption accounted for 94% of the liner carbon footprint

[c] Active ingredient is abbreviated a.i

CO_2e. Digging, hauling, and loading harvested trees and removal of culls contributed 6.267 kg CO_2e/marketable tree.

When the system is examined from the perspective of combined materials and equipment use for specific operations

Table 2 Contribution of equipment activities (diesel consumption) to the carbon footprint (Global Warming Potential, GWP, kilogram of CO_2e) during the field production phase of a 5-cm caliper, spade-dug, red maple tree

Activity (times over production cycle)	Hours per hectare (h/ha)	Diesel use (L/h)	Diesel/marketable tree[a] (L)	GWP (kg CO_2e)/ marketable tree[b]
Cover crop—fallow year	3.16	15.6698	0.0264	0.0704
Land preparation	3.16	15.6698	0.0264	0.0704
Transplanting	3.16	15.6698	0.0264	0.0704
Seeding between rows	1.43	15.6698	0.0119	0.0318
Pruning and staking	55.35	4.4652	0.1317	0.3513
Fertilizing (8 times)	12.64	4.4652	0.0307	0.0802
Mowing (16 times)	23.72	8.4226	0.1064	0.2840
Cultivation (12 times)	31.62	8.4226	0.1419	0.3786
Herbicide application (14 times)	27.68	8.4226	0.1242	0.3314
Insecticide application (21 times)	44.48	8.4226	0.1996	0.5325
Digging with tree spade	125.14	15.8675	1.0579	2.8226
Hauling and loading	250.26	8.3072	1.1076	2.9552
Removal of culls	20.34	16.9253	0.1834	0.4894
Irrigation (4 times)	23.72	15.1416	0.1915	0.5105
Total kg CO_2e/tree				8.9788

[a] Assuming 5% shrinkage due to plant death or unacceptable quality from total of 1,976 trees/ha

[b] Assuming 2.668 kg CO_2e/L of diesel fuel (http://www.epa.gov/oms/climate/420f05001.htm)

and general overhead to the field nursery gate, it is apparent that harvesting accounts for the vast majority of GWP inputs during field production (Fig. 2). Harvesting accounted for 7.134 kg CO_2e/tree or 56% of the GWP investment during field production. Fertilization, weed management, insect management, irrigation, land preparation and planting, and staking and pruning accounted for 12%, 9%, 4%, 4%, 3%, and 3% of the GWP investment during field production, respectively. Although a total of 12.798 kg CO_2e would be invested from input materials, equipment use during field production and associated overhead activities, an estimated 12.1 kg CO_2 would be sequestered by the growing tree. Therefore, field production processes and materials contributed 0.840 kg CO_2e. However, transport of the finished tree 386 km to the customer (4.040 kg CO_2e/tree) and 32 km to the landscape site (2.525 kg CO_2e) and equipment use in transplanting the tree (0.808 kg CO_2e) would contribute significantly to the carbon footprint of the tree entering the use phase. Therefore, transportation and transplanting would contribute 7.374 kg CO_2e (36%) to the total GWP investment of the finished product in the landscape (20.678 kg CO_2e/tree).

The weighted positive impact of carbon storage on GWP during the use phase for a red maple transplanted into a favorable environment was calculated to be 901 kg CO_2 (Fig. 3). The projected rate of increase in the accumulated, weighted carbon sequestration decreased as the tree matured, following a normal growth curve. The vast majority (95%) of the positive, direct impact on the carbon footprint of the red maple was estimated to occur during the first 50 years in the landscape. The carbon investment in the take down and disposal of the tree was calculated to be 92.9 kg CO_2e. Therefore, the net positive impact of this product on the atmospheric GHG after production, transplanting, use phase and end-of-life activities was estimated to be 800 kg CO_2e, 97 times more than the combined negative GWP impact of production, transport, and transplanting.

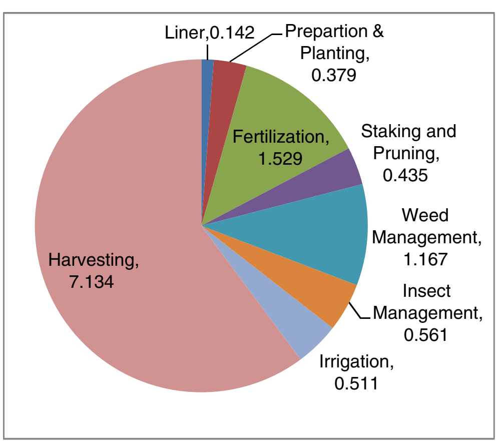

Fig. 2 The impact of specific system components (materials plus equipment use) on the carbon footprint (kilogram of CO_2e) of a 5-cm caliper red maple tree during the field production phase to the farm gate

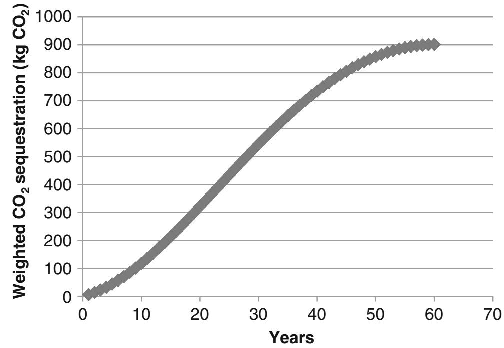

Fig. 3 Accumulated, weighted (based on a 100-year assessment period) GWP impact of sequestered CO_2 during the 60-year use phase of a 5-cm caliper red maple tree planted in the landscape

The potential use-phase impact of red maple could vary significantly with planting site, human activity pressures, required maintenance and end-of-life protocols. The survival rate of trees in more stressful urban environments would be expected to be less than assumed in this study (McPherson and Simpson 1999). Additional research is necessary to quantify potential effects of a range of environmental and physical factors on carbon sequestration in the use and end-of-life phases. For example, it has been reported that 18–24% of sequestered carbon in hardwoods is in the root system (McPherson and Simpson 1999), and this fits within the range published elsewhere (IPCC 2006; Mokany et al. 2006). It has also been reported that 80% of the carbon in roots left in the soil after tree removal is converted to other forms of carbon in the soil for long-term storage (McPherson and Simpson 1999). If these relationships are applied in this model, at least 500 kg of the CO_2 sequestered to the roots over the 60 years would remain in the rhizosphere at the site beyond the 100-year assessment period. However, due to the lack of definitive published data on this subject specific for the lower Midwest of the USA, this was not included in the current LCA.

The sensitivity analysis of GWP input variables revealed that a 10% increase in a given variable would result in at least a 1% increase in the total CO_2e investment for seven of the 72 separate variables included in the production phase. For the production phase (cutting-to-landscape), the variable with the greatest impact potential was CO_2 sequestration during production followed by transportation to the customer. A 10% increase in sequester CO_2 during production would result in a15% decrease in the carbon footprint. Increasing transportation distance to the landscape by 10% would result in an 8% increase in the carbon footprint. A 10% increase in nitrogen fertilizer during production would result in a 2% increase in the cutting-to-landscape carbon footprint. A 10% increase in the overhead would result in a 1% increase in the total CO_2e investment while a 10% increase in equipment use for transplanting would increase total CO_2e investment by 1%. When examining the aggregates of the life cycle phases

in the model, the model is most sensitive to CO_2 sequestration during the use phase, CO_2e investments in take down and disposal, followed by CO_2e investments during production and sequestration during production, in order of impact. A 10% change in sequestration during the use phase would result in an 11% change in the life cycle carbon footprint.

An important element of LCA is the ability to query the model relative to the impact of alternative input materials or processes. In the current model, if a modified 35-hp tractor allowed mowing the grass between rows as fertilizer, herbicide and/or insecticide applications were made and during cultivation within rows, that could eliminate up to 16 mowing passes (23.72 h/ha) through the field in the four growing seasons. This would reduce the CO_2e investment by 0.284 kg CO_2e/tree (3% of equipment use impact during field production).

The total GWP per kilogram of N for ammonium nitrate (14.35 kg CO_2e/kg N) was calculated to be 83% greater than the GWP per kilogram of N from urea (7.85 kg CO_2e/kg N). Simply substituting urea for ammonium nitrate as the source of N fertilization during field production would reduce the CO_2e investment by 0.646 kg CO_2e/tree and decrease the cutting-to-landscape carbon footprint by 8% to 7.567 kg CO_2e/tree.

If the finished product was shipped one-third less distance to the customer (257 km vs 386 km), the cutting-to-landscape carbon footprint would be reduced by 16% (1.346 kg CO_2e) to 6.867 kg CO_2e/tree. This alternative speaks to the weight and volume of this product and GWP benefits from buying local.

If there was a 10% cull rate instead of the 5% assumed for the field production phase, there would be 0.794 kg CO_2e added to the footprint of each of the 1,778 marketable trees/ha. This represents a 6% increase in CO_2e investments in each marketable tree. However, the 0.794 kg CO_2e/tree increased investment per marketable tree from a 10% cull rate during field production instead of a 5% cull rate represents a 10% increase in the tree's cutting-to-landscape carbon footprint to 9.007 kg CO_2e.

LCA has proven to be a valuable tool in analyzing the individual input components in the field production of a shade tree. It will allow nursery managers to make informed decisions about the various elements of the operation. Consumers can be informed about the relative GWP impact of system components such as transportation and make informed purchasing decisions driven by environmental concerns. Data generated from such analyses can also document the dramatically positive impact of shade trees on potential climate change. LCA analyses of additional nursery production systems and crops, including other environmental impact and economic factors, are required to attain a critical mass of information to help guide company and industry-level business strategies.

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